Direct Numerical Simulations of Isotropic and Post-Shock Turbulence Interacting with a Shock Wave

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We have conducted some of the largest Direct Numerical Simulations (DNS) to date of "isotropic turbulence" and "post-shock turbulence" passing through a normal shock wave. Such configurations are relevant in many practical applications and also represent unit problems for shock and re-shock phenomena in Richtmyer-Meshkov instability. We address for the first time the post-shock turbulence interacting with the shock wave. The inflow isotropic turbulence is generated using auxiliary forced compressible turbulence simulations with prescribed supersonic background speed. The inflow database for post-shock turbulence is collected from simulations of isotropic turbulence–shock wave interaction. Preliminary low-resolution results are presented here. We consider a shock wave with moderate strength (Mach = 1.2). Upstream of the shock wave, the microscale Reynolds number is 15, and the turbulence Mach numbers is 0.15 and 0.25. The behavior of the shocked and re-shocked turbulence is investigated by varying compressibility and Kolmogorov length scale of incoming turbulence. We present consistent results with previous studies on weakly compressible isotropic turbulence. Turbulent kinetic energy and spanwise vorticity fluctuations are amplified while passing through a shock wave, and the turbulence length scales decrease.

The interaction of shock waves with turbulence occurs in many interesting problems, including supernova explosions, inertial confinement fusion, and internal and external flow in hypersonic flight and propulsion. The coexistence of shock waves with some background turbulence is an almost unavoidable feature that creates complicating effects (anisotropy of the background turbulence, mean-flow gradients, oblique or bent shock wave, unsteady separation, etc.) so that a detailed understanding remains far from reach. For this reason, several studies [1–3] have focused on the interaction between isotropic turbulence and a normal shock wave as one of the basic phenomena involved in these flows. The purpose of this study is to produce flow statistics for turbulence modeling and to develop relevant theory for shocked and re-shocked turbulence by conducting accurate direct numerical simulations of corresponding problems.

In this study, all the relevant turbulence scales, as well as shock wave structures, are resolved as a solution of the Navier-Stokes equations without applying turbulence-model and shock-capturing methods using CFDNS code [4]. A plane steady shock wave satisfying Rankine-Hugoniot relations is specified as an initial condition in the middle of the domain. Compressible Navier-Stokes equations for a Newtonian fluid with perfect gas assumption are nondimensionalized by upstream density, temperature, and speed of sound. Prandtl number is taken as Pr = 0.75 and the ratio of specific heats is 1.4. It is important to provide fully developed and realistic turbulence at the upstream of the shock wave. Incoming isotropic turbulence is generated using auxiliary forced compressible turbulence simulation with prescribed supersonic background velocity. In this manner we avoid the ambiguity and limitations of using Taylor's hypothesis, which is typically applied for temporally decaying isotropic turbulence to generate spatially decaying turbulence. We apply the linear turbulence forcing method [5–7] in triply periodic domain. After reaching a statistically stationary state, plane data in the middle of the domain perpendicular to the streamwise direction is collected and used as the inflow boundary condition for the isotropic turbulence interacting with shock wave simulation. Plane data behind the shock wave is collected and used as the inflow condition for another post-shock turbulence interaction with shock wave problem.

A range of isotropic turbulence simulations is conducted for various forcing wavenumbers and Kolmogorov length scales. Here we present preliminary results on the shocked and re-shocked turbulence. Figure 1 shows an instantaneous streamwise velocity field of isotropic turbulence and shock wave interaction. The velocity field is nondimensionalized with the speed of sound of upstream flow. The streamwise velocity fluctuates around a specified supersonic Mach number (1.2) in the upstream of the shock wave, and after being suppressed by the shock wave the velocity fluctuates around subsonic speed. Figure 2 compares the variation of Reynolds stress across the shock wave among different

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turbulent Mach numbers and shocked and re-shocked turbulence. To investigate post-shock turbulence and shock wave interaction, plane data behind the shock wave is saved to match the turbulent Mach number of inflow isotropic turbulence. Red solid and black dot-dashed lines represent strong and weak post-shock turbulence, respectively, interacting with the shock wave. Blue dashed and violet dotted lines respectively represent strong and weak shocked isotropic turbulence. For both shocked and re-shocked turbulence, Reynolds stresses are less amplified for stronger turbulence. For a similar turbulence strength, isotropic turbulence is less amplified than anisotropic post-shock turbulence. This result is consistent with the synthetic anisotropic turbulence interacting with the shock wave in [8]. Further analysis will be conducted with the ongoing high-resolution simulations.

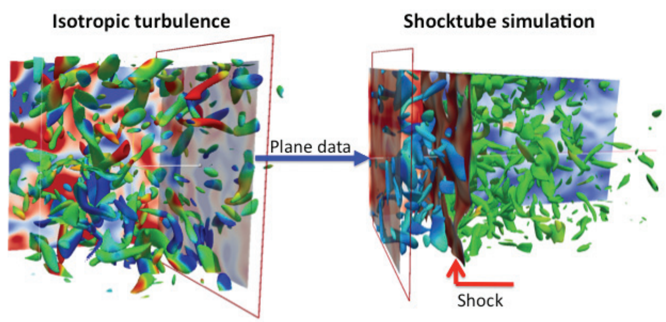

Fig. 1. Diagram of shocktube inlet condition. Data recorded from the isotropic turbulence simulations is an inlet condition for the shocktube domain, which is used to study shock-turbulence interactions.

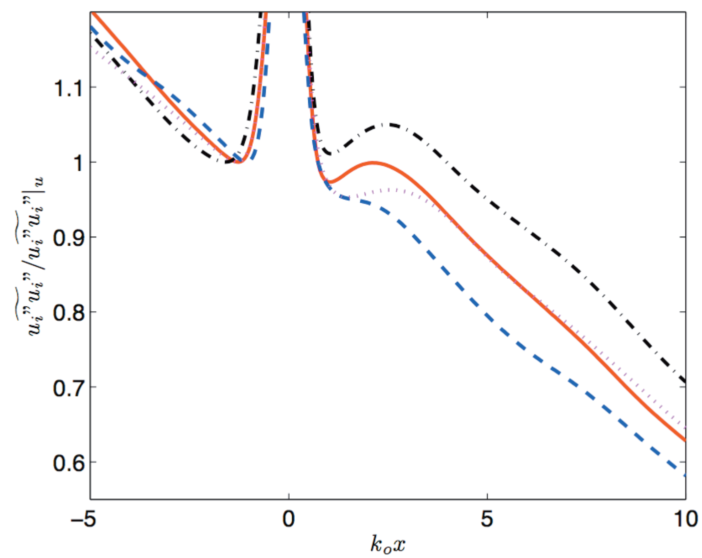

Fig. 2. Reynolds stress. The effect of changing turbulent Mach number and the difference between shocked and re-shocked turbulence. Red solid and black dot-dashed lines respectively represent strong and weak re-shocked turbulence. Blue dashed and violet dotted lines respectively represent strong and weak shocked isotropic turbulence.

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